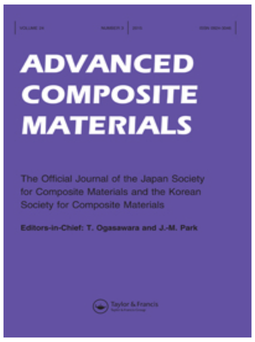

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Relationship between the drilling condition and the damage (delamination) zone of glass-fiber-reinforced plastic composites

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Delamination is one of the main defects observed from the drilling of composite materials, and can be an important limiting factor for the use of composite materials. In this study, the delamination area factor for GFRP (Glass Fiber Reinforced Plastic) drilling was proposed to quantify the practical delamination zone via digital imaging of the damage zone around the hole and by calculating the damage zone by pixel. From the tests, it was concluded that a higher drill feed rate reduced the delamination zone and the cutting speeds have no influence on the delamination zone. Also, the proposed delamination area factor was more suitable and useful for delamination zone evaluation than the existing delamination factor.

Keywords: drilling; delamination; cutting speed; feed rate

1. Introduction

Composites are increasingly used for their excellent mechanical characteristics. The fabrication of large or complicated structures using composites, such as airplane bodies, mostly requires composite–composite or composite–metal joint structures. The joint structures for composites are largely divided into adhesive and mechanical joint structures. Mechanical joints require additional mechanical processing such as drilling to provide a solid connection using bolts or rivets. However, the processing may damage the material surface and cause mechanical defects, including strength degradation or stress concentration.[1]

Delamination is one of the main defects observed from the drilling of composite materials, and can be an important limiting factor for the use of composite materials. It causes stress concentration or micro-cracks, and significantly reduces the advantages of composite materials. Accordingly, diverse approaches have been implemented to reduce delamination. First, quantitative evaluation was introduced to examine the effects of main cutting conditions and drilling types.[2–5]

In the drilling of composite materials, the delamination at the entry and exit of the hole was evaluated via the delamination factor F_d using the maximum crack length from the hole center (F_d, i.e. the ratio of the maximum diameter D_{max} in the damage zone to the hole diameter D).[2,3] Diverse approaches have been implemented to analyze the effect of the delamination factor according to the drilling condition. Chen

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et al. [3] proposed a concept of a delamination factor that ensures easy analysis and comparison of delamination in CFRP (Carbon Fiber Reinforced Plastic) drilling, and tested the changes in the cutting power according to the delamination in drilling. From the test results, they proposed a condition for minimizing the delamination according to the tool shape or the drilling condition. Mohan et al. [4] determined the optimum cutting condition using the Taguchi technique to minimize delamination in GFRP (Glass Fiber Reinforced Plastic) drilling. They showed that the feed rate, cutting speed, and specimen thickness significantly affect delamination, and that a higher cutting speed and a lower feed rate can normally minimize delamination and lead to better surface roughness and a longer tool life. Ramesh et al. [5] analyzed the relative effects of the feed rate, cutting speed, and torque using ANOVA in non-laminated GFRP drilling. The delamination increased in proportion to the cutting speed, and a higher feed rate reduced the delamination damage on the surface. Zitoune et al. [6] analyzed the effects of the drill diameter, main spindle rotation speed, feed rate, torque, surface roughness, etc. in CFRP and aluminum laminated material drilling. In addition, they analyzed the shape of the chips according to the drilling conditions. The inner surface roughness of the machined hole increased with the increase in the feed rate, and was degraded in proportion to the cutting speed. The delamination factor that was used in these studies was the maximum crack length from the hole center, and had a limitation in effectively quantifying the characteristics of the entry and exit of the drilling hole.

In this study, the delamination area factor for GFRP drilling was proposed to quantify the practical delamination zone via digital imaging of the damage zone around the hole and by calculating the damage zone by pixel. Moreover, the characteristics of the delamination zone were analyzed according to the feed rate, main spindle rotation speed, and drilling time. To consider the actual drilling condition, the change in the delamination zone was analyzed with the backplate sufficiently supported, and the existing delamination factor F_d was compared with the proposed delamination area factor.

2. Delamination zone quantification and drilling

2.1. *Delamination zone quantification*

Figure 1 shows the diagram of the damage zone that is usually observed at the entry and exit of the hole in composite material drilling. Equation (1) is the most widely used formula for the damage zone quantification, and is called the *delamination factor*. That is, the delamination factor (F_d) is the ratio of the maximum diameter of the delamination zone (D_{max}) to the machined hole diameter (D_o).

$$F_d = \frac{D_{max}}{D_o} \tag{1}$$

However, as shown in Figure 1(a) and (b), the delamination factor is constant, but the delamination area significantly differs. Therefore, there is a limitation in quantifying the actual delamination zone using the delamination factor in Equation (1).

In this study, to quantify the delamination zone, the magnified digital image of the damage zone around the hole was taken, and the image data were processed by pixel for the calculation. Because the diameter in the image is proportional to the number of pixels after the imaging of the damage zone, the maximum diameter of the delamination zone (D_{max}) is as follows:

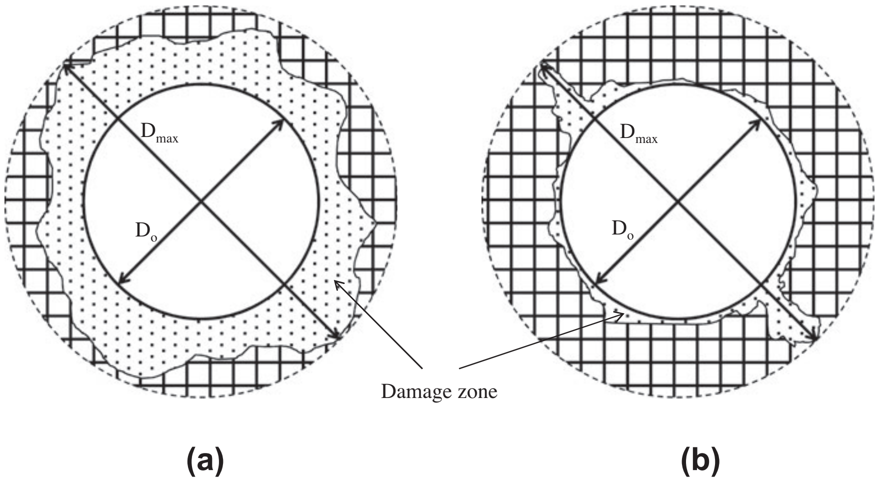

Figure 1. Schematic diagram of the damage zone.

$$D_{max} = D_o \frac{N_p(D_{max})}{N_p(D_o)} \tag{2}$$

wherein $N_p(D_{max})$ and $N_p(D_o)$ are the number of pixels for the maximum diameter of the delamination zone and the machined hole diameter, and are obtained from the image processing tool. Accordingly, the existing delamination factor equation (Equation (1)) is expressed as Equation (3).

$$F_d = \frac{N_p(D_{max})}{N_p(D_o)} \tag{3}$$

If the numbers of pixels for the delamination zone area (A_d) and the hole area (A_o) are $N_p(A_d)$ and $N_p(A_o)$, respectively, the areas in the image will be proportional to the number of appropriate pixels. Therefore, the delamination zone area is calculated as shown in Equation (4).

$$A_d = A_o \frac{N_p(A_d)}{N_p(A_o)} \tag{4}$$

The delamination area (A_d) is difficult to calculate because the damage zone at the entry and exit of the machined hole is very irregular. However, the delamination area can be easily and accurately calculated using Equation (4), which uses the number of pixels from the imaging results.

In this study, the delamination area factor F_{da} was proposed to effectively quantify the damage zone. The delamination factor refers to the ratio of the delamination area to the hole cross-section area (Equation (5)). The delamination area factor is expressed as Equation (6) by applying Equations (4) to (5).

$$F_{da} = \frac{A_o + A_d}{A_o} \tag{5}$$

$$F_{da} = 1 + \frac{N_p(A_d)}{N_p(A_o)} \tag{6}$$

The newly proposed delamination area factor can clearly distinguish the damage zone in Figure 1(a) and (b). Therefore, it can overcome the limitation of the existing delamination factor and easily calculate the delamination zone and the delamination factor using only the number of pixels, even when the area cannot be geometrically calculated.

2.2. Drilling

The material for the glass-fiber specimen in the composite material drilling test was GEP224 (four-harness satin weave glass/epoxy prepreg). The 0.25 mm-thick prepregs were laminated at a lamination angle of $[0/90]_{14s}$ to fabricate a 7 mm-thick specimen. A high-speed steel drill with a diameter of 8 mm was used. To examine the characteristics of the machined surface according to the drilling conditions such as the feed rate, cutting speed, and number of processing times, 50 holes were machined for each specimen according to the drilling conditions. An acrylic support was installed at the bottom to ensure similar delamination at the entry and exit of the hole when the drill was moving in the vertical direction. To minimize the vibration effect, the vise was attached as closely as possible to the specimen edge (Figure 2). In addition, drilling was conducted in the wet processing method with cutting oil to prevent the thermal effect from changing the number of processing times.

The following are the drilling conditions that were used in this study to precisely analyze the delamination zone characteristics according to the drilling condition. The feed rate f (mm/rev) was changed in six steps at the reference cutting speed of $V_c = 21.31$ ($f = 0.0125$, 0.025, 0.05, 0.10, 0.20, and 0.40), and the cutting speed V_c (m/min) was changed at the reference feed rate of $f = 0.15$ ($V_c = 15.08$, 21.31, 30.16, and 42.65). To analyze the characteristics according to the number of processing times, 50 holes were consecutively machined for each specimen, and the 12 holes in the rectangular box in Figure 3 (H4, H7, H10, H17, H20, H23, H30, H33, H36, H43, H46, and H49) were sampled to evaluate the delamination factor. One drill was used for each test condition to analyze the machining characteristic according to each test condition.

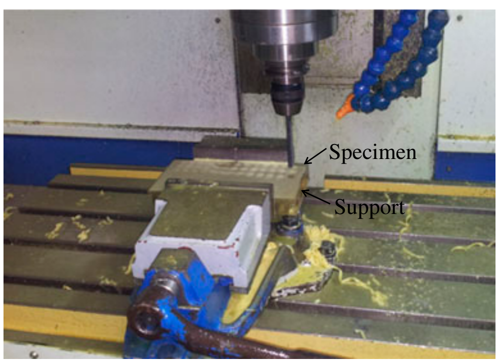

Figure 2. Experimental drill machining.

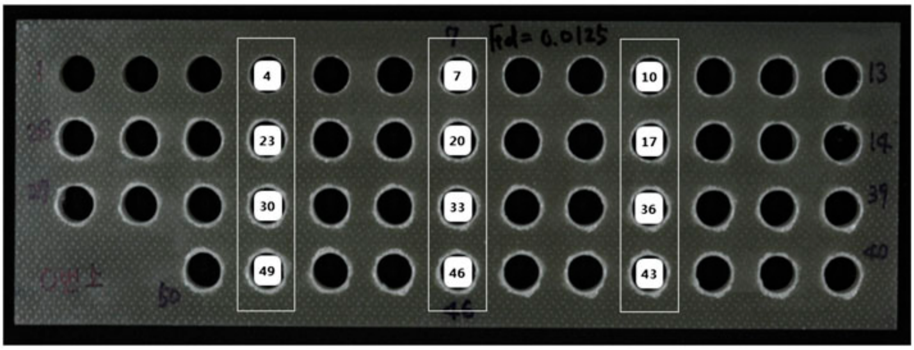

Figure 3. Measurement holes to quantify the delamination factors.

3. Discussion and analysis

According to the drilling condition of the GFRP material, the characteristics of the delamination zone were analyzed at the entry and exit of the drilling hole. Photoshop (PS6.0 Extended) was used for image processing, and the delamination factor and the delamination area factor in Chapter 2 were calculated to identify their relationship to the drilling condition. Table 1 shows the drilling condition that was used in this study.

3.1. Feed rate and number of processing times

Table 2 shows the results of the analysis of the delamination zones of the 12 drilling holes when the feed rate was 0.0125 mm/rev (F1), which provides the number of pixels for the diameter and area obtained from the image processing and the calculated delamination factor and the delamination area factor. Figure 4 shows, in a graph, the delamination factor and the delamination area factor that were calculated according to the six-step feed rate conditions (F1–F6).

As shown in Figure 4, a higher feed rate significantly reduced the delamination factor F_d and the delamination area factor F_{da}. As described in Chapter 2, the specimen was fully fixed with fixtures and support, and the increase in the feed rate did not increase the vibration. It seems that the decrease in the cutting force application time caused by the increase in the feed rate led to less damage by delamination at the entry and exit of the hole.

Table 1. Test condition, test name, and test value.

Test condition	Test name	Value
Feed rate (mm/rev) at $V_c = 21.31$ m/min	F1	*0.0125*
	F2	*0.025*
	F3	*0.05*
	F4	*0.1*
	F5	*0.2*
	F6	*0.4*
Cutting speed (m/min) at $f = 0.15$ mm/rev	V1	*15.08*
	V2	*21.31*
	V3	*30.16*
	V4	*42.65*

Table 2. Pixels, delamination factor, and area delamination factor by test.

Hole no.	$N_p(D_o)$	$N_p(D_{max})$	$N_p(A_o)$	$N_p(A_d)$	F_d	F_{da}
H4	*118*	*133*	*14,062*	*2027*	*1.13*	*1.19*
H7	*117*	*136*	*14,668*	*2745*	*1.16*	*1.25*
H10	*118*	*135*	*14,492*	*2849*	*1.15*	*1.26*
H17	*117*	*141*	*15,756*	*3554*	*1.20*	*1.33*
H20	*117*	*144*	*16,412*	*3639*	*1.23*	*1.33*
H23	*118*	*144*	*16,422*	*3974*	*1.22*	*1.36*
H30	*117*	*142*	*16,002*	*3988*	*1.21*	*1.37*
H33	*118*	*146*	*16,863*	*4375*	*1.24*	*1.40*
H36	*118*	*148*	*17,294*	*4471*	*1.25*	*1.40*
H43	*117*	*154*	*18,636*	*4611*	*1.31*	*1.43*
H46	*117*	*147*	*16,985*	*4849*	*1.26*	*1.45*
H49	*117*	*147*	*17,149*	*4963*	*1.26*	*1.46*

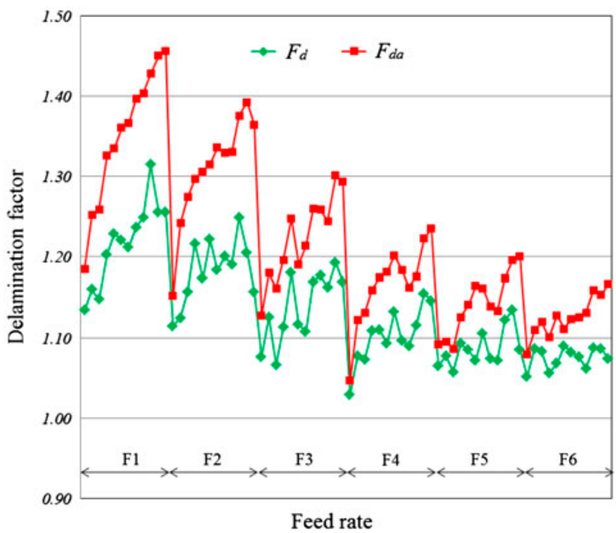

Figure 4. Delamination factor (F_d) and delamination area factor (F_{da}) by feed rate variation at the entry hole.

In addition, an increase in the number of processing times increased the delamination factor in a specimen, because the drill wear increased the damage zone as the processing continued. In addition, in each feed rate zone, the increase in the number of processing times increased the delamination zone, which showed that the delamination area factor graph was clearer than the existing delamination factor graph. This is seemingly because the calculated area was close to the actual delamination area because the number of pixels was used, as described in Chapter 2. Figure 5 shows the distribution of the delamination factor obtained according to the feed rate change at the drilling hole exit. The distributions of the delamination factor and the delamination area factor were similar to those at the hole entry, as was the range of the delamination factor. This is seemingly because the specimen was uniformly machined with a support fixed to it, and because in one hole, the drill wear difference between the entry and exit was not so significant as to cause a change in the delamination factor.

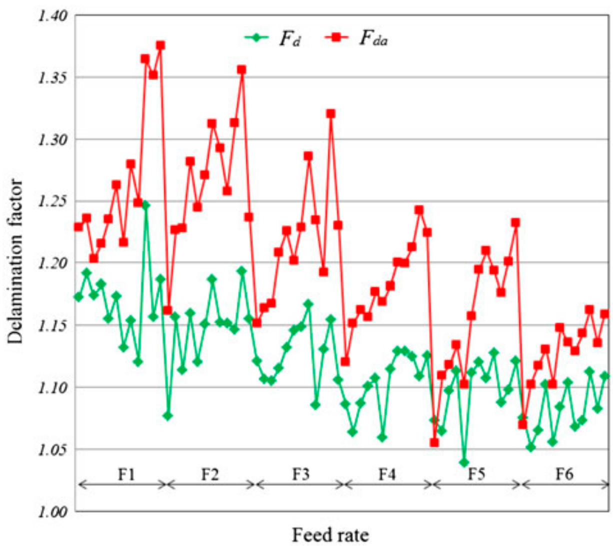

Figure 5. Delamination factor (F_d) and delamination area factor (F_{da}) by feed rate variation at the exit hole.

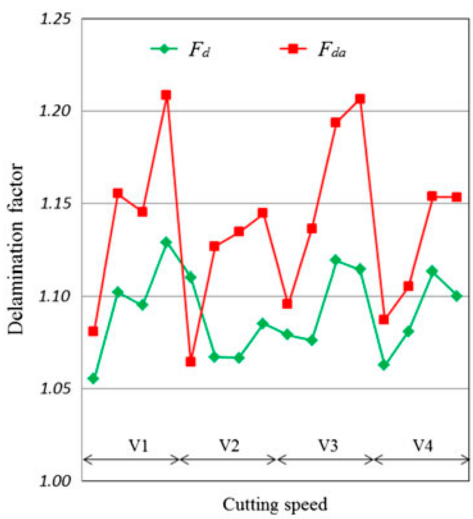

Figure 6. Delamination factor (F_d) and delamination area factor (F_{da}) by cutting speed variation at the entry hole.

3.2. Cutting speed

Figure 6 shows the delamination factor and the delamination area factor calculated at the entry of the drilling hole according to the four-step cutting speed (V1–V4) condition. The four holes in the rectangular box in Figure 3 (H7, H20, H33, H46) were sampled to evaluate the delamination factor. In Figure 6, both the delamination factor and

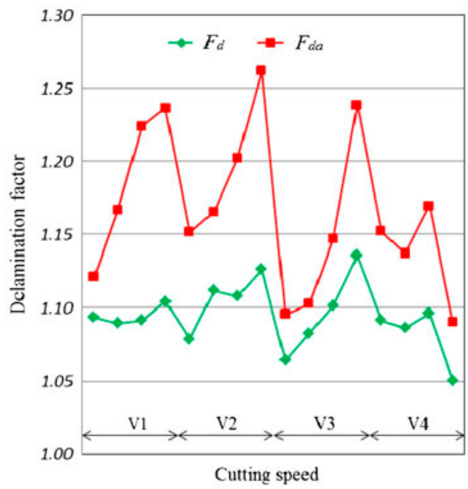

Figure 7. Delamination factor (F_d) and delamination area factor (F_{da}) by cutting speed variation at the exit hole.

the delamination area factor show no significant change according to the increase in the cutting speed. It seems that both factors are hardly affected by the cutting speed. Only one cutting speed condition, the increase in the number of processing times, increased the delamination factors. This is seemingly because the drill wear increased the delamination zone as the processing continued. Figure 7 shows the delamination factor and the delamination area factor at the hole exits, which are similar to the cutting speed characteristics at the hole entry. As in the case of the feed rate, the change in the delamination area factor more clearly expressed the trend than the change in the existing delamination factor.

4. Conclusion

In this study, the delamination zone at the hole entry and exit in the GFRP material was comparatively analyzed according to the drilling condition. A new delamination area factor (F_{da}) for more closely expressing the damage zone at the entry and exit of the drilling hole was derived and used. Specimens were fabricated and drilling was conducted according to each test condition, and the delamination zone at the entry and exit of the drilling hole was evaluated by applying the existing F_d and F_{da}. The results of the drilling and evaluation showed that a higher drill feed rate reduced the F_d and F_{da}, and a higher number of processing times increased the F_d and F_{da}. With the change in the cutting speed, the F_d and F_{da} showed almost no change. The changes in the delamination factors were analyzed according to the three drilling conditions, and the F_{da} had a more sensitive and consistent trend than the F_d. This shows that F_{da} is more suitable and useful for delamination zone evaluation than the existing delamination factor.

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